Synthesis and Use of 7-Substituted Norbornadienes† for the Preparation of Prostaglandins and Prostanoids

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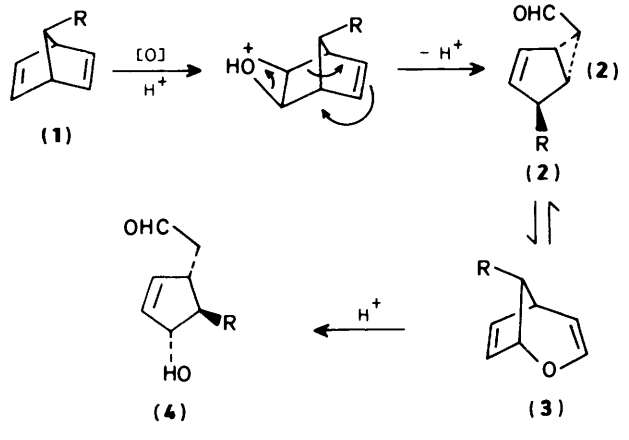
Syntheses of 7-substituted norbornadienes from 7-t-butoxy- and 7-halogeno-norbornadienes are described. Rearrangement of the products in the presence of peracetic acid gives bicyclic aldehydes (**2**) in equilibrium with enol ethers (**3**) which are hydrolysed to hydroxycyclopentenylacetaldehydes (**4**), and converted into key intermediates for the synthesis of prostaglandins and their analogues. Syntheses of prostaglandin J analogues with n-hexyl and phenyl groups replacing the ω-side-chain are described.

Oxidative rearrangement of a 7-substituted norbornadiene (**1**) to give the bicyclic aldehyde (**2**), in equilibrium (*via* an oxa-Cope rearrangement) with the enol ether (**3**), followed by hydrolysis to the hydroxy-aldehyde (**4**), as shown in Scheme 1, is in principle an attractive, versatile route for the synthesis of prostaglandins and analogues. The aldehyde (**4**) has the correct stereochemistry about the cyclopentane ring; the substituent R could represent a natural prostaglandin ω-side-chain or another group; and the aldehyde group could be used to synthesise the upper side-chain present in prostaglandins A–F (Wittig reaction) or the substituted tetrahydrofuran ring present in prostaglandins I (aldol reaction and halogenoetherification). Indeed, we have reported in a preliminary communication[1] that this route can be utilised to prepare the hydroxy aldehyde (**5**), which has previously been used to synthesise 6-β-prostaglandin I_1,[2] prostaglandin I_2 (prostacyclin),[3] and prostaglandin J_2[4] (formerly described as 9-deoxa-9,10-dehydroprostaglandin D_2 or isoprostaglandin A_2).[5] In this paper we describe the scope and limitations of methods for preparing 7-alkyl-, 7-aryl-, 7-alkenyl-, and 7-alkynylnorbornadienes, and how these compounds can be used to prepare a wider range of prostaglandins and analogues.

Story has reported that the reaction of norbornadiene with t-butyl peroxybenzoate, catalysed by copper(I) bromide, gives



Scheme 1.

† Throughout this paper, the term norbornadiene refers to bicyclo-[2.2.1]hepta-2,5-diene (IUPAC alternative: 8,9,10-trinorbornadiene).

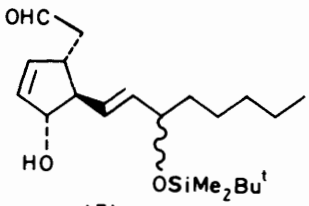
7-t-butoxynorbornadiene (**6**)[6]‡ Furthermore, treatment of 7-t-butoxynorbornadiene with methylmagnesium iodide or phenylmagnesium bromide in boiling benzene gave the corresponding 7-substituted norbornadiene (**7**) or (**8**).[7] We have confirmed this report, and prepared other 7-alkylnorbornadienes [(**9**)—(**11**)] by this route. However, all attemps to extend the method to alkenyl (**17**) or alkynyl (**20** and **21**) Grignard reagents failed. Analogous reactions of cuprates such as (**19**) were also unsuccessful.

Possible alternative starting materials for the synthesis of 7-alkenylnorbornadienes were 7-chloronorbornadiene (**12**), with a better nucleofuge at the 7-position, and 7-formylnorbornadiene (**13**), which would be a convenient substrate for further elaboration by way of Wittig reactions.

7-t-Butoxynorbornadiene is converted into 7-chloronorbornadiene (**12**) by reaction with acetyl chloride[8] or dry hydrogen chloride;[9] the latter method is preferred, as by the former it is difficult to avoid contamination of the product by acetyl chloride. Most nucleophilic substitution reactions of 7-chloronorbornadiene give tricyclic compounds (Scheme 2);[10] and with butyl-lithium, 7-butylnorbornadiene (**9**) was only a minor product;[11] however, reaction with the appropriate Reformatsky reagent gave the ester (**14**).[12] In our hands, reaction of 7-chloronorbornadiene with the Grignard reagent (**17**), the organolithium compound (**18**), or the cuprate (**19**) all failed to give the desired product (**24**) (or its analogue with CPh_3 in place of $SiMe_2Bu^t$). However, a copper(I)-catalysed reaction with the alkynylmagnesium bromide (**20**) gave the corresponding 7-alkynylnorbornadiene (**26**) in 72% yield.[13] This intermediate (**26**) was converted into the corresponding 7-*E*-alkenylnorbornadiene (**24**) as shown in Scheme 3. Each stage proceeded cleanly, in high yield,§ but it was clearly desirable

‡ **CAUTION!** In carrying out this preparation[6b] we have experienced one explosion and one runaway reaction during the final distillation. The absence of peroxide contaminant(s) should be ensured before heating is applied, and the distillations should be carried out behind safety screens. 7-t-Butoxynorbornadiene is now commercially available (Lancaster Synthesis Ltd.).

§ For the reduction with lithium aluminium hydride, careful attention to the experimental conditions is needed to avoid some reduction of a ring double bond and allene formation (S. Jones, University of Salford, unpublished work). Lower reaction temperatures with tetrahydrofuran (THF) as solvent are recommended in order to favour reduction of alkynols to alkenols (J. W. Blunt, M. P. Hartshorn, M. H. G. Munro, L. T. Soong, R. S. Thompson, and J. Vaughan, *J. Chem Soc., Chem. Commun.*, 1980, 820). By using the stoicheiometric amount of lithium aluminium hydride given in the Experimental section reduction of the ring double bond can be avoided.



(5)

(6) X = OBu^t

(7) X = Me

(8) X = Ph

(9) X = Bu

(10) X = $n-C_6H_{13}$

(11) X = $n-C_8H_{17}$

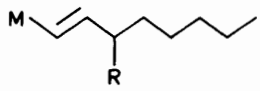
(12) X = Cl

(13) X = CHO

(14) X = CH_2CO_2Et

(15) X = 

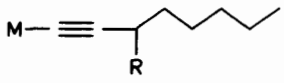
(16) X = I



(17) M = MgX, R = $OCPh_3$

(18) M = Li, R = $OSiMe_2Bu^t$

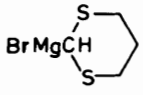
(19) M = $LiCu(C{\equiv}CC_3H_7)$, R = $OSiMe_2Bu^t$



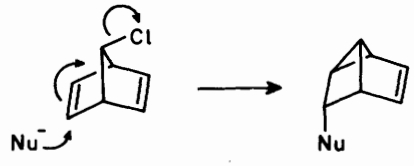
(20) M = MgBr, R = $OSiMe_2Bu^t$

(21) M = MgBr, R = H

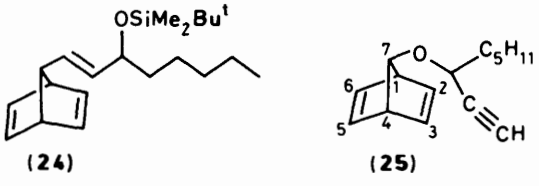
(22) M = MgBr, R = OMgBr



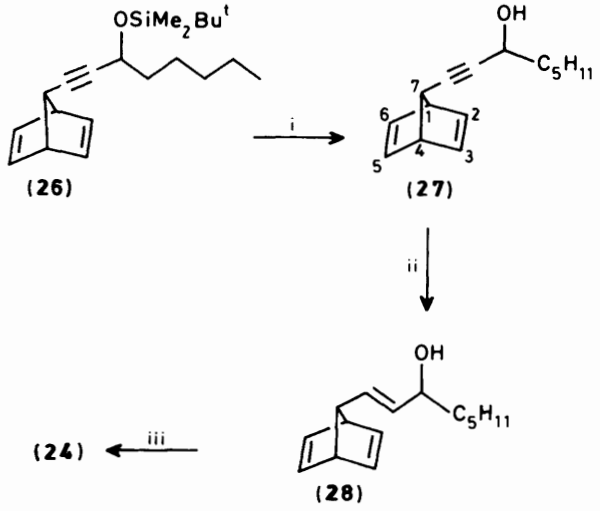
(23)



Scheme 2.



(24) (25)



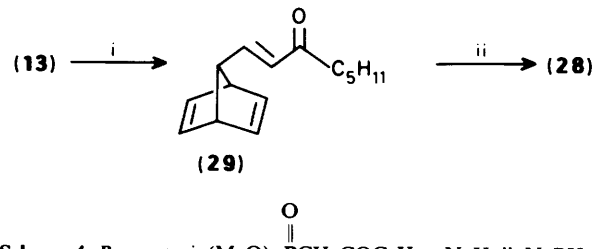
(26) (27) (28)

Scheme 3. *Reagents:* i, HF, CH_3CN; ii, $LiAlH_4$; iii, TBDMSCl, imidazole

to avoid the protection–reaction–deprotection–reaction–protection sequence. An attempt to cut out two stages by a reaction of 7-chloronorbornadiene with the reagent (**22**) (prepared from oct-1-yn-3-ol with 2 mol equiv. of ethylmagnesium bromide) gave the alkynyl ether (**25**) instead of the desired acetylenic alcohol (**27**).

The synthesis of 7-formylnorbornadiene (**13**) has been reported by Stapersma and Klumpp.[14] The 7-alkenylnorbornadiene (**28**) was first synthesised from this aldehyde (**13**) *via* a Wadsworth–Emmons reaction to give the enone (**29**), followed by borohydride reduction as shown in Scheme 4, but other routes to this intermediate were more practical.

As an alternative approach to 7-formylnorbornadiene (**13**), attempts were made to prepare the dithiane precursor (**15**). Reaction of 7-chloronorbornadiene with the Grignard reagent

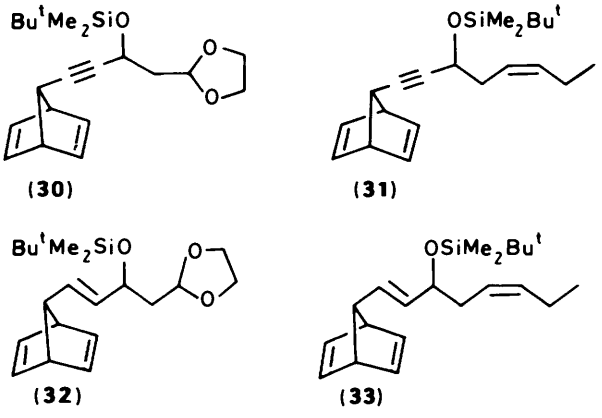


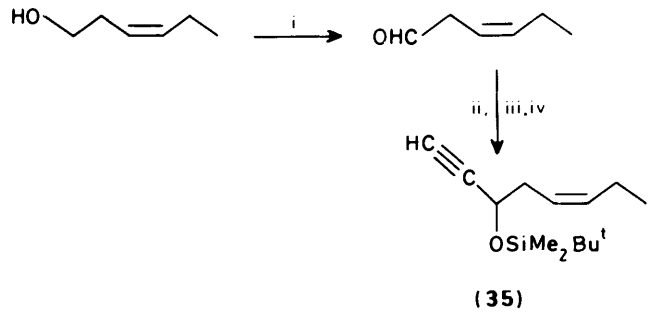
Scheme 4. *Reagents:* i, $(MeO)_2PCH_2COC_5H_{11}$; NaH; ii, $NaBH_4$

(23) prepared from 2-lithio-1,3-dithiane and magnesium bromide gave the required 7-(1,3-dithianyl)norbornadiene (15) but the yield (~30%) did not justify further work.

Success in obtaining a direct coupling of a prostaglandin side-chain to the 7-position of norbornadiene was finally achieved by a reaction of the side-chain heterocuprate (19) with 7-iodonorbornadiene (16). 7-Iodonorbornadiene is unstable,[15] but it could be prepared *in situ* and caused to react at −78 °C. Although the yields so far obtained by this reaction are modest (20%), and its scope has not been explored, it is potentially the method of choice for synthesising 7-alkenylnorbornadienes.

We have also prepared the potentially useful 7-alkynyl-norbornadienes (30) and (31) by the Grignard route, and have reduced them to the corresponding alkenes (32) and (33) (as





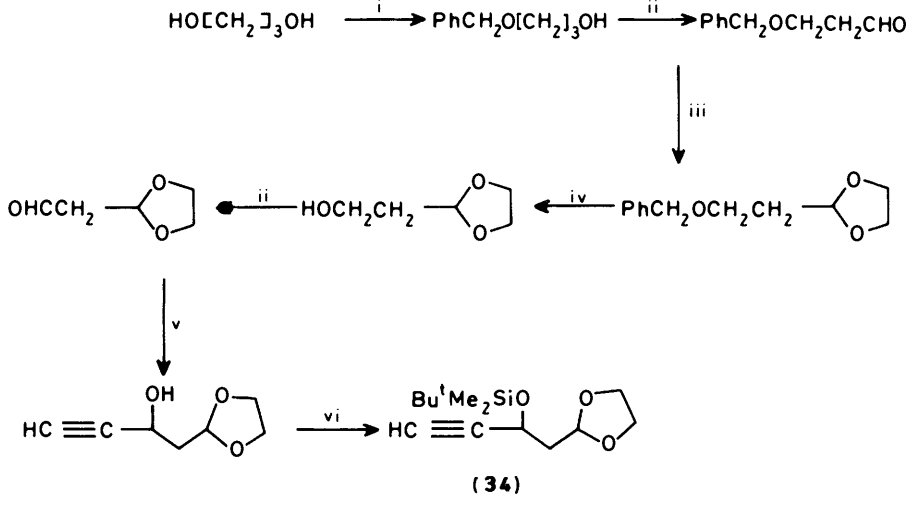
Scheme 6. *Reagents:* i, PCC; ii, HC≡CMgBr; iii, H_3O^+; iv TBDMSCl, imidazole

in Scheme 3). The syntheses of the alkynes (34) and (35), precursors for the Grignard reagents, are shown in Schemes 5 and 6.

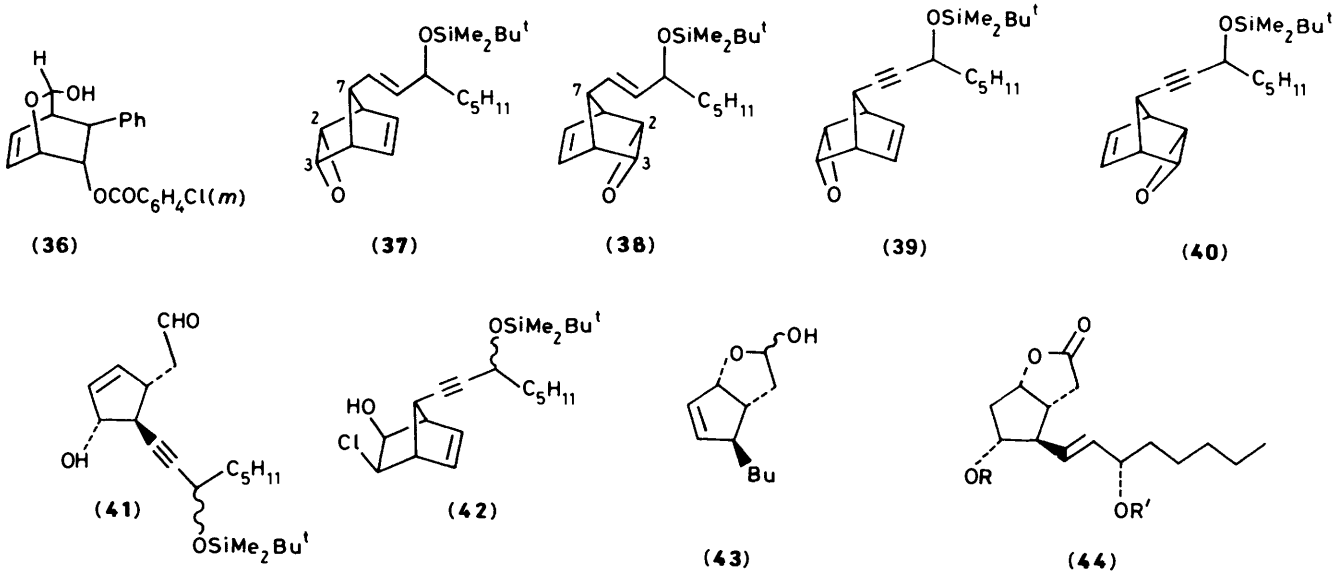
Peracid Reactions of 7-Substituted Norbornadienes followed by Hydrolysis.—Meinwald *et al.*[16] observed that the oxidation of bicyclo[2.2.1]hepta-2,5-diene (1; R = H) with buffered peracetic acid gives bicyclo[3.1.0]hex-2-ene-6-*endo*-carbaldehyde (2; R = H) and this work was later extended to 7-methyl-[17] and 7-phenyl-norbornadiene (1; R = Me and Ph).[18] The authors postulated the intermediacy of the expected *exo*-epoxide which rapidly undergoes acid-catalysed rearrangement by rearside attack of the transannular bond. Since product (2) is in dynamic equilibrium with the enol ether (3) by an oxa-Cope rearrangement, hydrolysis provides a route to 4-hydroxy-cyclopenten-2-ylacetaldehydes (4).

To attain the correct stereochemistry for prostaglandin synthesis it is necessary for mono-epoxidation to occur with stereo- and regio-selectivity in an *exo-anti* manner relative to the 7-substituent on the bicyclo[2.2.1.]heptadiene ring system. While the literature precedents favour this mode of reaction for 7-methyl- and 7-phenyl-norbornadiene, 7-t-butoxynorbornadiene has been reported to epoxidise in an *exo-syn* manner.[19] Padwa and Koehn found that with *m*-chloroperbenzoic acid (MCPBA) and 7-phenylnorbornadiene, over-epoxidation led to the formation of the 5-oxabicyclo[2.2.2]oct-2-ene (36) as the major product.[18]

Peracetic acid oxidations of the 7-substituted norbornadienes



Scheme 5. *Reagents:* i, NaH, $C_6H_5CH_2Cl$, DMF; ii, PCC; iii, $HOCH_2CH_2$ OH, benzene; iv, Na–liq. NH_3; v, C_2H_5MgBr, HC≡CH, THF; vi, TBDMSCl, imidazole

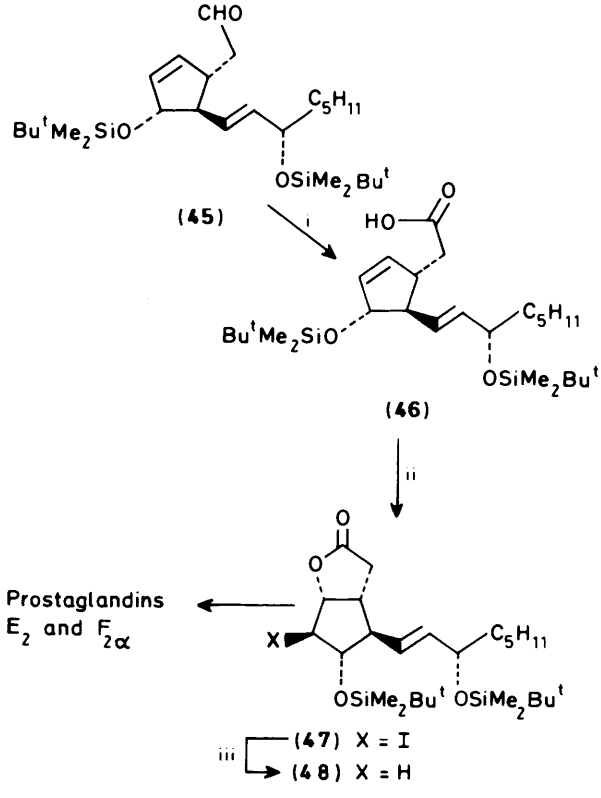


(8)—(11), (24), (26), (31), and (33) have all given rise to the 4-*exo*-substituted bicyclo[3.1.0]hex-2-ene-6-*endo*-carbaldehydes (2) [in dynamic equilibrium with the respective enol ethers (3)] as major products. T.l.c. indicated the presence of minor components which were assumed to be the *endo*-epoxides [*e.g.*, (37) and (38)] but were difficult to separate at this stage. In the case of the oxidation of the 7-alkenylnorbornadiene (20), firmer evidence was obtained that the minor products did include the *endo*-epoxides (37) and (38), although they were not fully characterised. Thus, a mixture of two components, only just separable on t.l.c., was obtained, which showed virtually no carbonyl absorption in its i.r. spectrum, but whose mass spectrum showed it to comprise isomers of the bicyclic aldehyde (2). The mixture's ^{1}H n.m.r. spectrum showed signals at δ_H 3.46 and 3.66 in a ratio of *ca.* 1:3, attributed to the oxirane ring protons (2-, 3-H) and signals at δ_H 2.86 and 3.01 in a similar ratio, attributed to 7-H. A sample obtained after treatment of the reaction product with aqueous hydrochloric acid (see below) was further examined for nuclear Overhauser effects in the n.m.r. spectrum. Irradiation of a signal at δ_H 3.01 produced a strong positive n.O.e. enhancement of the signal at δ_H 3.66, implying that the major epoxide was the *endo-anti-isomer* (37).

In contrast to the work of Padwa and Koehn,[18] 7-phenylnorbornadiene was oxidised and rearranged in sodium carbonate-buffered peracetic acid, and 4-*oxo*-phenylbicyclo[3.1.0]-hex-2-ene-6-*endo*-carbaldehyde (2; R = Ph) was the major product (70.5%) and was isolated as a crystalline solid. In the other cases, (9)—(11), (24), (26), (31), and (33), the oily reaction mixtures were hydrolysed in a two-phase system of methylene dichloride and 2M-hydrochloric acid to allow ready isolation of the respective cyclopentenylacetaldehydes (4), (5), (41), (58), and (59) with the correct stereochemistry for further elaboration to the prostanoids. Under these conditions the *endo*-epoxides (39) and (40) formed from (26) did not react and were separated by chromatography from the more polar hydroxycyclopentenylacetaldehyde (41) and chlorohydrin (42).[13] It is also relevant to note that although the 7-substituted norbornadienes (24), (26), (31), and (33) have unsaturation in the side-chain, peracetic acid oxidation gives the required prostaglandin prescursors (4) as major products.

As an alternative to the two-phase system for hydrolysis of the enol ethers, oxalic acid dihydrate in methylene dichloride at room temperature was used for hydrolysis of the butyl enol ether (3; R = Bu) and the lactol (43) was isolated, presumably by acid-catalysed rearrangement of the allylic alcohol (4; R = Bu).[20]

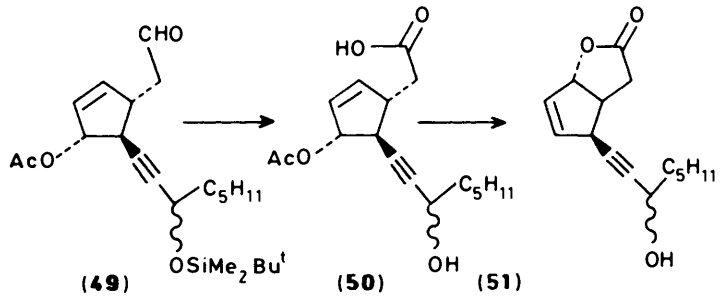
5-[3′-(Dimethyl-t-butylsilyloxy)oct-1′-enyl)-4-hydroxycyclopent-2-enyl]acetaldehyde (5) can be elaborated to give 6-β-PGI$_1$,[2] PGI$_2$,[3] and PGJ$_2$;[4] this intermediate (5) can also be converted into useful γ-lactone derivatives (44). Thus protection of the 4-hydroxy group as the silyl derivative (45), followed by oxidation with silver oxide, gave the carboxylic acid (46) (Scheme 7). Cyclisation using iodine in the presence of potassium iodide gave the iodo lactone (47) which, on hydro-



Scheme 7. *Reagents:* i, Ag_2O, NaOH, H_2O; ii, KI_3, Et_2O, $NaHCO_3$; iii, Bu_3SnH, PhH

deiodination with tri-n-butyltin hydride, furnished the lactone (**48**). This lactone has been utilised in the synthesis of PGE_2,[21] $PGF_{2\alpha}$,[22] and analogues.[23,24]

In summary the synthesis and oxidative rearrangement of 7-substituted norbornadienes provide a versatile route to the biologically important prostaglandins and their analogues.

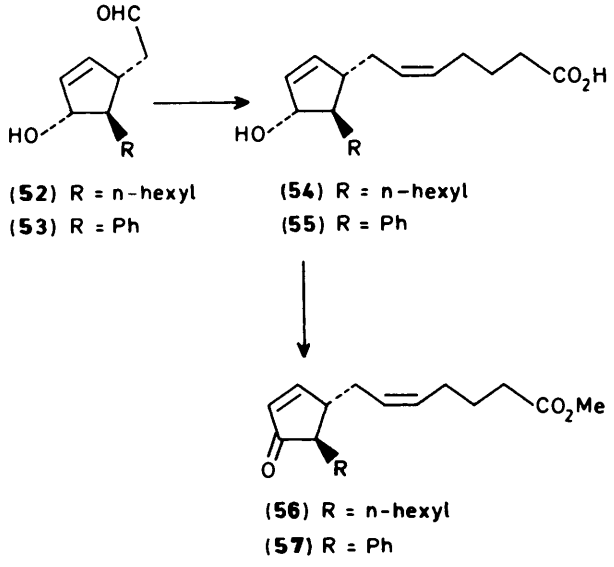


(**49**) (**50**) (**51**)

Scheme 8.

Elaboration of the alkynylcyclopentenylacetaldehyde (**41**) as shown in Scheme 8 demonstrates an entry to the A series of prostaglandins. Thus acetylation of the hydroxy group to give compound (**49**), followed by oxidation of the aldehyde group with silver oxide and work-up with hydrochloric acid, led to the hydroxy carboxylic acid (**50**). Cyclisation with elimination of the acetoxy group gave the bicyclic lactone (**51**) capable of expansion to the PGA series by the procedure of Corey and Moinet.[25]

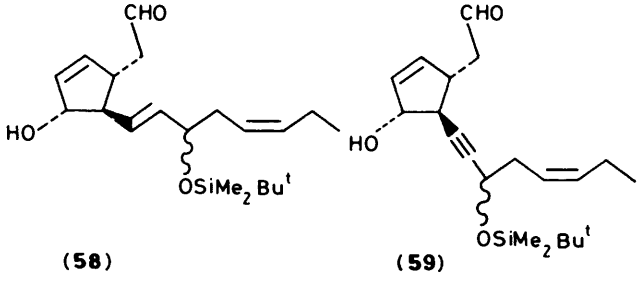
7-Substituted norbornadienes also provide access to PGJ analogues. Prostaglandin J_2 is formed from prostaglandin D_2 at physiological pH and temperature and its Δ^{12} isomer is formed from PGD_2 enzymically.[4] Both isomers show anti-tumour properties, so the study of analogues appears worthwhile. Thus chain extension of the hexyl- and phenyl-cyclopentenylacetaldehydes (**52**) and (**53**) by the requisite Wittig reaction gave the acids (**54**) and (**55**) which were esterified and oxidised with Collins' reagent to give the PGJ analogues (**56**) and (**57**) (Scheme 9).



(**52**) R = n-hexyl
(**53**) R = Ph
(**54**) R = n-hexyl
(**55**) R = Ph
(**56**) R = n-hexyl
(**57**) R = Ph

Scheme 9.

Attempts to provide 13,14-didehydroprostaglandin J_2 were unsuccessful owing to a shift of the hydrogen at C-12 to give 12,13-didehydroprostaglandin J_2.[13]



(**58**) (**59**)

Experimental

M.p.s were determined using the capillary tube method. I.r. spectra were recorded on a Perkin-Elmer 257, a Perkin-Elmer 377, or a Unicam SP200 spectrometer for neat films unless otherwise stated. ^1H N.m.r. spectra were recorded on a Varian EM360 or a Bruker Spectraspin (250 MHz) spectrometer ($CDCl_3$ solvent). ^{13}C N.m.r. spectra were measured with a Varian CFT 20 spectrometer; multiplicities from off-resonance spectra are given in parentheses. Electron-impact (e.i.) mass spectra and accurate mass determinations were obtained on AEI-MS12 and MS902S spectrometers: chemical ionisation (c.i.) mass spectra were obtained on a VG7070 mass spectrometer using ammonia as the carrier gas. Column chromatography was performed using Merck Kieselgel (60H) Art 7729 or 7736 unless stated otherwise; t.l.c. was accomplished using Polygram $SilG/UV_{254}$ plates supplied by Camlab. Anhydrous magnesium sulphate was used as a drying agent for solutions in organic solvents. Light petroleum refers to the fraction boiling at 60—80 °C unless otherwise stated; ether refers to diethyl ether.

Preparation of 7-Alkyl- and 7-Phenyl-norbornadienes.—The general procedure of Story and Fahrenholtz[7] was used to prepare 7-butylnorbornadiene (**9**) (83%), 7-hexylnorbornadiene (**10**) (88%), 7-octylnorbornadiene (**11**) (88%), and 7-phenylnorbornadiene (**8**) (80%) by treatment of the respective Grignard reagent with 7-t-butoxynorbornadiene (**6**) in refluxing benzene. 7-Butylnorbornadiene (**9**) was obtained as an oil after chromatography on silica and elution with light petroleum–ether (4:1), $\delta_H(CDCl_3)$ 1.0—1.2 (9 H, m, Bu), 2.5 (1 H, br m, 7-H), 3.35 (2 H, m, 1- and 4-H), 6.6 (2 H, t, *J* 2 Hz, 2- and 3-H), and 6.8 (2 H, t, *J* 2 Hz, 5- and 6-H); δ_C(p.p.m.) 144 (d, C-2 and -3), 139 (d, C-5 and -6), 87 (d, C-7), 53 (d, C-1 and -4), 30 (m), 29 (m), 22 (m), and 13 (m, n-C_4H_9) (Found: M^+, 148.1244. Calc. for $C_{11}H_{16}$: *M*, 148.1252).

7-Hexylnorbornadiene (**10**) was purified by medium-pressure chromatography on silica to give an oil after elution with 15% ethyl acetate in light petroleum (b.p. 40—60 °C), $\delta_H(CDCl_3)$ 0.9 (3 H, t, CH_3) 1.3 (10 H, m, $[CH_2]_5$), 2.4 (1 H, m, 7-H), 3.25 (2 H, t, 1- and 4-H), 6.6 (2 H, t, 2- and 3-H), and 6.8 (2 H, t, 5- and 6-H) (Found: M^+, 176; C, 88.55; H, 11.4%; $C_{13}H_{20}$ requires *M*, 176; C, 88.57; H, 11.4%).

7-Octylnorbornadiene (**11**) was obtained as an oil after chromatography on silica, $\delta_H(CDCl_3)$ 1.1 (17 H, m, n-C_8H_{17}), 2.5 (1 H, m, 7-H), 3.2 (2 H, m, 1- and 4-H), 6.55 (2 H, t, *J* 2 Hz, 2- and 3-H), and 6.8 (2 H, t, *J* 2 Hz, 5- and 6-H); $\nu_{max.}$(film) 2 900, 1 460, 730, and 650 cm^{-1}; (*m/z*, %) 204 (0.4), 105 (27), and 91 (100) (Found: C, 88.2; H, 11.8. $C_{15}H_{24}$ requires C, 88.2; H, 11.8%).

Preparation of Anhydrous Magnesium Bromide.[26]—A solution of bromine (1.45 g, 9.1 mmol) in dry THF (4 ml) was added dropwise to a suspension of magnesium turnings (0.33 g, 13.8 mmol) in dry THF (10 ml) under N_2. A vigorous reaction occurred and a two-phase system separated with a clear upper layer and a pale orange-yellow lower layer. The upper layer was syringed off and its volume noted. The remaining orange layer theoretically contained anhydrous magnesium bromide (5 mmol) in THF (4 ml).

Preparation of 7-(1,3-*Dithian*-2-*yl*)*bicyclo*[2.2.1]*hepta*-2,5-*diene* (**15**).—A solution of anhydrous magnesium bromide (1.5 ml) (effectively 1.8 mmol) was syringed into a reaction flask containing 2-lithio-1,3-dithiane solution prepared *in situ via* addition of n-BuLi (0.24 g) in n-hexane in dry THF (10 ml) at 0 °C to a stirred solution of 1,3-dithiane (0.94 g, 7.83 mmol) in THF (10 ml). The mixture slowly turned brown and was stirred for 30 min. 7-Chlorobicyclo[2.2.1]hepta-2,5-diene (**12**) (0.5 g, 3.95 mmol) was added and the mixture was stirred for a further 2 h at 0 °C, and the solution was then heated for 1 h at 35—40 °C.

The mixture was poured into saturated ammonium chloride (40 ml) and the aqueous phase was extracted with ether (3 × 50 ml). The organic extracts were combined, washed with water (2 × 25 ml), and dried. Filtration and evaporation of the excess of solvent under reduced pressure afforded a pale orange oil (2.5 g). Column chromatography with silica (50 g) and 5—10% ethyl acetate–light petroleum (40—60 °C) as eluant gave the *title compound* (0.25 g, 30%) as a pale yellow oil, R_F 0.72 [20% EtOAc–light petroleum (40—60 °C)]; $\nu_{max.}$ 1 159 and 912 cm^{-1}; δ_H 2.2 (2 H, m, CH_2), 2.9—3.1 (5 H, m, 7-H and 2 × CH_2), 3.65 (2 H, q, 1- and 4-H), 4.2 (1 H, d, 8-H), 6.6 (2 H, t, 5- and 6-H), and 6.8 (2 H, t, 2- and 3-H) (Found: M^+, 210.3647. $C_{11}H_{14}S_2$ requires *M*, 210.3651).

Preparation of 7-(3′-*Oxo-oct*-1′-*enyl*)*bicyclo*[2.2.1]*hepta*-2,5-*diene* (**29**) *from* 7-*Formylnorbornadiene* (**13**).—Dimethyl 2-oxo-heptylphosphonate (1.35 g, 6.127 mmol) in dimethoxyethane (DME) (16.5 ml) was added to a suspension of sodium hydride (0.25 g, 10.42 mmol) (previously freed from an oil dispersion by washing with light petroleum) in DME (66 ml). The mixture was stirred for 1 h at room temperature to form a thick white precipitate which was cooled to 0 °C. 7-Formylbicyclo[2.2.1]-hepta-2,5-diene (**13**) (0.69 g, 5.75 mmol) prepared by the method of Stapersma and Klumpp[14] was extremely sensitive to air and was dissolved without rigorous purificiation in ether (10 ml) and added to the above Wittig reagent dropwise. The reaction mixture was stirred at 0 °C for 0.5 h and then at room temperature for 2.5 h, then was neutralised with glacial acetic acid. Extraction with ether (4 × 25 ml) followed by successive washing with water (4 × 25 ml) and brine (25 ml) and evaporation of the dried ($MgSO_4$) ether extract gave a crude 7-(3′-oxo-oct-1-enyl)bicyclo[2.2.1]hepta-2,5-diene (**29**) as an oil, R_F 0.65 (silica; 30% ether–light petroleum) which was purified by medium-pressure chromatography on silica with 15% ether in light petroleum as eluant to give the *title enone* (**29**) (28.6% from 7-chloronorbornadiene); $\nu_{max.}$ 1 710, 1670, and 1 620 cm^{-1}; $\delta_H(CDCl_3)$ 0.9 and 1.17 (9 H, m, $[CH_2]_3Me$), 2.50 (2 H, t, *J* 8 Hz, 4′-H_2), 3.23 (1 H, d, *J* 8 Hz, 7-H), 3.53 (2 H, br s, 1- and 4-H), 6.03 (1 H, d, *J* 15.6 Hz, 2′-H), 6.62 (2 H, br s, 5- and 6-H), 6.90 (2 H, br s, 2- and 3-H), and 7.55 (1 H, m, 1′-H) (Found: M^+, 216.1514. $C_{15}H_{20}O$ requires *M*, 216.1513).

Preparation of 7-(3′-*Hydroxyoct*-1′-*enyl*)*bicyclo*[2.2.1]*hepta*-2,5-*diene* (**28**).—A solution of 7-(3′-oxo-oct-1′-enyl)bicyclo-[2.2.1]hepta-2,5-diene (**29**) (0.683 g, 3.16 mmol) in ethanol (60 ml) was added to a stirred suspension of sodium borohydride (0.119 g, 3.16 mmol) in ethanol (60 ml) at 0 °C. The reaction was monitored by t.l.c. and further quantities of sodium borohydride (0.683 g, 3.16 mmol) were added after 15 min and 1 h. The product, R_F 0.33 (silica; 30% ether in light petroleum), was purified by medium-pressure chromatography on silica; elution with 15% ether in light petroleum gave 7-(3′-*hydroxyoct*-1′-*enyl*)*bicyclo*[2.2.1]*hepta*-2,5-*diene* (**28**) as an oil (0.5 g, 66%), $\nu_{max.}$ 3 300—3 400br (OH) and 964 cm^{-1} (*trans* olefin); $\delta_H(CDCl_3)$ 0.87 (3 H, t, *J* 7 Hz, 8′-H_3), 1.3 (8 H, m, $[CH_2]_4Me$), 3.10 (1 H, d, *J* 7 Hz, 7-H), 3.42 (2 H, m, 1- and 4-H), 3.98 (1 H, q, *J* 7 Hz, 3′-H), 5.45 (1 H, dd, *J* 15 and 7 Hz, 2′-H), 5.7 (2 H, dd, *J* 15 and 7 Hz, 5- and 6-H), and 6.82 (2 H, br s, 2′- and 3′-H) (Found: M^+, 218.1670. $C_{15}H_{22}O$ requires *M*, 218.1670).

Silylation of 7-(3′-*Hydroxyoct*-1′-*enyl*)*bicyclo*[2.2.1]*hepta*-2,5-*diene*. (**28**).—The alcohol (**28**) (0.40 g, 1.83 mmol) was stirred overnight with t-butyldimethylsilyl chloride (TBDMSCl) (0.55 g, 3.68 mmol) and imidazole (0.55 g, 8.08 mmol) in dimethylformamide (DMF) (70 ml). T.l.c. over silica showed that the reaction was complete and the pure *silyl ether* (**24**) [R_F 0.8 (30% ether in light petroleum)] was isolated by medium-pressure chromatography over silica and elution with 10% ether in light petroleum, $\delta_H(CDCl_3)$ 0.10 (6 H, s, $SiMe_2$), 0.90 (12 H, m, 4 × Me), 1.1—1.5 (8 H, m, $[CH_2]_4$), 3.10 (1 H, d, *J* 7.5 Hz, 7-H), 3.42 (2 H, m, 1- and 4-H), 3.98 (1 H, q, *J* 7 Hz, 3′-H), 5.45 (1 H, dd, *J* 15 and 7.5 Hz, 1′-H), 5.65 (1 H, dd, *J* 15 and 7.5 Hz, 2′-H), 6.64 (2 H, br s, 5- and 6-H), and 6.82 (2 H, t, *J* 1.5 Hz, 2- and 3-H) (Found: M^+, 332.2534; C, 75.5; H, 11.2%. $C_{21}H_{36}OSi$ requires *M*, 332.2534; C, 75.8; H, 10.9%).

Preparation of 7-(*Oct*-1′-*yn*-3′-*yloxy*)*bicyclo*[2.2.1]*hepta*-2,5-*diene* (**25**).—A solution of ethyl bromide (8.62 g, 79.1 mmol) in THF (7.5 ml) was added to a suspension of magnesium turnings (1.90 g, 79.2 mmol) in dry THF (12 ml) and the mixture was stirred for 25 min after the initial effervescence had ceased. A solution of oct-1-yn-3-ol (4.98 g, 39.5 mmol) in THF (15 ml) was added and a steady stream of ethane was evolved. The solution was heated to 60 °C in an oil-bath for 1.5 h and Cu^ICl (250 mg) was added. The pale green solution was cooled to room temperature. A solution of 7-chlorobicyclo[2.2.1.]hepta-2,5-diene (**12**) (5.0 g, 39.5 mmol) in THF (15 ml) was added and the solution was stirred for 20 min, at room temperature and at 70—75 °C for 1.5 h. The reaction mixture was cooled to room temperature, and added to water (50 ml), and the organic phase was extracted with ether (3 × 50 ml). The ethereal layers were combined and washed with water (2 × 25 ml) and dried. Filtration and evaporation afforded a dark orange oil (4.9 g). Flash chromatography using silica (90 g, Art. 9385) and elution with 15% ethyl acetate–light petroleum (40—60 °C) gave the *title compound* (3.97 g, 47%) as a pale yellow oil, R_F 0.69 [15% ethyl acetate–light petroleum (40—60 °C)]; δ_H (90 MHz) 0.9 (3 H, t, Me), 1.4—1.5 (8 H, m, $[CH_2]_4$), 2.4 (1 H, d, 1′-H), 3.3—3.5 (3 H, m, 1-, 4-, and 7-H), 3.85 (1 H, s, 3′-H), 6.5 (2 H, t, 5- and 6-H), and 6.6 (2 H, t, 2- and 3-H); δ_C 140.1 (d), 139.8 (d), 137.7 (d), 137.1 (d),

136.6 (d), 88.2 (s), 73.05 (d), 72.6 (d), 67.8 (d), 62.1 (d), 35.6 (t), 31.7 (t), 29.5 (t), 24.8 (t), and 13.79 (q) (Found: C, 83.45; H, 9.5. $C_{15}H_{20}O$ requires C, 83.3; H, 9.3%).

In another experiment, using a 1:1:1 molar ratio of ethylmagnesium bromide, octynol, and 7-chloronorbornadiene, the yield was 86%.

Preparation of 7-(3′-*Hydroxyoct*-1′-*ynyl*)*bicyclo*[2.2.1]*hepta*-2,5-*diene* (**27**) *from* 7-[(3′-*Dimethyl*-t-*butylsilyloxy*)*oct*-1′-*ynyl*]-*bicyclo*[2.2.1]*hepta*-2,5-*diene* (**26**).—(a) *Desilylation using tetra*-n-*butylammonium fluoride*. To a solution of silyl ether (**26**) (260 mg, 0.78 mmol) in dry THF (5 ml) was added tetra-n-butylammonium fluoride (1M in THF; 0.86 mmol). The brown solution was stirred for a few min at room temperature and then kept for 2 h, when t.l.c. indicated no more starting material remained. Hexane (5 ml) was added, and the mixture was reduced in volume under reduced pressure to *ca.* 3 ml and applied directly to a short-path column (silica, Art. 7729; 5 g). By elution with ethyl acetate in hexane (1—30%), the *pure alcohol* (**27**) (132 mg, 78%) was obtained as an oil, R_F 0.46 (30% EtOAc–hexane); $\nu_{max.}$ 3 400br and 2 900 cm^{-1}; δ_H 0.9 (3 H, t, *J* 6 Hz, Me), 1.38 (6 H, m, 5′-, 6′-, and 7′-H_2), 1.65 (2 H, m, 4′-H_2), 1.82 (1 H, d, *J* 7 Hz, OH), 3.06 (1 H, m, 7-H), 3.64 (2 H, q, 1- and 4-H), 4.28 (1 H, q, 3′-H), 6.7 (2 H, t, 5- and 6-H), and 6.75 (2 H, t, 2- and 3-H), (Found: M^+, 216.1512; C, 83.2; H, 9.3%. $C_{15}H_{20}O$ requires *M*, 216.1513; C, 83.3; H, 9.3%).

(b) *Desilylation using* HF *in acetonitrile*. A solution of the silyl ether (**26**) (500 mg, 1.51 mmol) in acetonitrile (10 ml) and HF (40% aqueous solution; 1.5 ml) was kept at room temperature and intermittently stirred for 20 min. Brine (20 ml) and ethyl acetate (50 ml) were added. The organic phase was washed successively with more brine (2 × 30 ml) and saturated aqueous sodium hydrogen carbonate. The aqueous washes were extracted with ethyl acetate (50 ml). The combined organic phases were dried, filtered, and evaporated to afford a yellow oil. Purification by short-path column chromatography (silica, Art. 7736; 20 g; eluant 2% ethyl acetate in light petroleum) afforded the alcohol (**27**) (260 mg, 79%) as an oil, identical with the product prepared by method (a).

Alternative Preparation of 7-(3′-*Hydroxyoct*-1′-*enyl*)*bicyclo*-[2.2.1]*hepta*-2,5-*diene* (**28**).—(a) To a solution of lithium aluminium hydride (73 mg, 1.94 mmol) in dry THF (10 ml) was added dropwise a solution of the alkynol (**27**) (84 mg, 0.388 mmol) in dry THF (10 ml). The solution was stirred under nitrogen at room temperature for 15 min, and then under reflux for 160 min. The reaction mixture was cooled to room temperature and water–THF was added judiciously until evolution of gas ceased. 2M-Sodium hydroxide was added, and the mixture was stirred for 1 h. Water (5 ml) was added followed by 2M-hydrochloric acid (7 ml) whereupon the solution reached pH 3. The products were extracted into ethyl acetate (2 × 50 ml), and the organic layers were washed successively with brine (30 ml) and water (30 ml). Brine (30 ml) was added to the combined aqueous layers, and the mixture was extracted with ethyl acetate. The combined organic layers were dried, filtered, and evaporated, leaving a pale yellow oil.

The oil was subjected to short-path column chromatography, eluant 5—10% ethyl acetate in hexane, to afford the trienol (**28**) (84 mg, 99%) as an oil identical with the product obtained previously.

(b) *'Direct' introduction of* 3-(*dimethyl*-t-*butylsilyloxy*)*oct*-1-*enyl substituent*. 7-Iodonorbornadiene (**16**)[15] was prepared from 6-chloronorbornadiene (**12**) under argon, immediately before use, as described by Franck–Neumann and Sedrati.[15] n-Butyl-lithium (1.6M in hexane; 1.38 ml) was added to a stirred solution of *trans*-3-(dimethyl-t-butylsilyloxy)-1-iodo-oct-1-ene (0.74 g) in dry ether (20 ml) at −78 °C. After 1 h, a solution of pent-1-ynylcopper(I) (0.26 g) and hexamethylphosphorous triamide (0.72 g) in dry ether (10 ml) was added. The reaction mixture was stirred at −78 °C during 1 h, and then added dropwise to a solution of 7-iodonorbornadiene (**16**) (0.5 g, 2.3 mmol) in ether (10 ml) at −78 °C. The mixture was kept at *ca.* −80 °C for 4 h. Saturated aqueous ammonium chloride (40 ml) was added. The organic layer was separated and stirred with ice-cold 1M-sulphuric acid (20 ml) and the resulting yellow precipitate was removed by filtration. The organic layer of the filtrate was washed with 8% w/v aqueous sodium hydrogen carbonate (20 ml), dried, and evaporated. Flash chromatography of the residue (silica; hexane) gave, as the major product, 7-[*trans*-3′-(dimethyl-t-butylsilyloxy)oct-1′-enyl]norbornadiene (**24**) (151 mg, 20%) as an oil, with i.r., ^1H n.m.r. and R_F identical with those of the material described above.

3-(*Dimethyl*-t-*butylsilyloxy*)-4-(1,3-*dioxolan*-2-*yl*)*but*-1-*yne* (**34**).—Sodium hydride (1.58 g, 66 mmol) was added during 15 min to an ice-cold solution of propane-1,3-diol (5.0 g, 66 mmol) in DMF (100 ml), and the mixture was stirred at 0 °C during *ca.* 30 min. Benzyl chloride (8.05 g, 64 mmol) was added, and the mixture was stirred at room temperature during 12 h. The mixture was filtered, and the solid residue was washed successively with water (50 ml) and ether (20 ml). Conventional work-up of the combined filtrate gave 3-benzyloxypropan-1-ol (6.53 g, 60%), b.p. 70—90 °C at 20 mmHg (lit.,[27] 172 °C/43 mmHg); δ_H 1.8 (2 H, m, CH_2), 2.6 (1 H, s, OH), 3.5—3.8 (4 H, m, 2 × OCH_2), 4.5 (2 H, s, PhCH_2), and 7.25 (5 H, s, C_6H_5).

A solution of 3-benzyloxypropan-1-ol (5.0 g, 30 mmol) in methylene dichloride (12 ml) was added in one portion to a stirred suspension of pyridinium chlorochromate (PCC) (13.0 g, 60 mmol) in methylene dichloride (100 ml). The mixture was stirred for 3 h. The solution was separated from the black insoluble material, which was extracted with ether (5 × 50 ml). The combined organic extracts were shaken vigorously, filtered through silica (10 g) and evaporated. The resulting orange oil was distilled to afford 3-benzyloxypropanal (4.0 g, 81%), b.p. 75—80 °C/20 mmHg (lit.,[28] 109 °C/30 mmHg); $\nu_{max.}$ 1 720 cm^{-1}; δ_H 2.6 (2 H, td, *J* 2 and 7 Hz, CH_2CHO), 3.75 (2 H, t, *J* 7 Hz, OCH_2CH_2), 4.5 (2 H, s, PhCH_2), 7.3 (5 H, s, C_6H_5), and 9.7 (1 H, t, *J* 2 Hz, CHO).

A mixture of ethane-1,2-diol (1.6 g), toluene-*p*-sulphonic acid (PTSA) (25 mg), 3-benzyloxypropanal (0.8 g, 4.9 mmol), and benzene (30 ml) was boiled in a Dean–Stark apparatus until removal of water was complete. After having cooled, the reaction mixture was shaken with saturated aqueous potassium carbonate (50 ml). Conventional work-up then gave 2-(2-*benzyloxyethyl*)-1,3-*dioxolane* (0.9 g, 89%), b.p. 80 °C/20 mmHg (Kugelrohr); δ_H 2.15 (2 H, m, CH_2CH_2CH), 3.7 (2 H, t, OCH_2-CH_2), 3.9—4.1 (4 H, m, 2 × ring OCH_2), 4.65 (2 H, s, $C_6H_5CH_2$), 5.15 (1 H, t, CH_2CH), and 7.45 (5 H, m, C_6H_5). (Found: M^+, 208.2006. $C_{12}H_{16}O_3$ requires *M*, 208.2009).

Sodium was added in portions to a stirred solution of 2-(2-benzyloxyethyl)-1,3-dioxolane (0.5 g, 2.4 mmol) in a mixture of liquid ammonia (200 ml) and dry THF (30 ml) until a blue colour persisted. An excess of solid ammonium chloride was added, and the ammonia was allowed to evaporate off. Ether (300 ml) was added and the solution was evaporated to leave 2-(2-*hydroxyethyl*)-1,3-*dioxolane** (0.25 g, 89%), $\nu_{max.}$ 3 640 cm^{-1}; δ_H 1.8 (2 H, m, $HOCH_2CH_2$), 2.6—2.7 (1 H br s, OH), 3.6 (2 H, t, CH_2OH), 3.9—4.1 (4 H, m, 2 × OCH_2), and 5.3 (1 H, t, CH_2CH) (Found: C, 51.2; H, 8.5. $C_5H_{10}O_3$ requires C, 50.8; H, 8.5%).

2-(2-Hydroxyethyl)-1,3-dioxolane (0.5 g, 4.2 mmol) was

* This compound has been reported (H. C. Brown and J. C. Chen, *J. Org. Chem.*, 1981, **46**, 3978), but was not characterised.

oxidised by PCC essentially as described above for 3-benzyloxypropan-1-ol, to give 2-(1,3-dioxolan-2-yl)ethanal (0.36 g, 74%), b.p. 90—98 °C/20 mmHg (Kugelrohr); $\nu_{max.}$ 1 730 cm^{-1}; δ_H 2.9 (2 H, m, CH_2CHO), 3.9—4.0 (4 H, m, 2 × OCH_2), 5.3 (1 H, t, CH_2CH), and 9.3 (1 H, t, CHO) (Found: $[M + 1]^+$ 117.1251. $C_5H_9O_3$ requires $[M + 1]$, 117.1249).

Acetylene was passed during 1 h at a rate of 15—20 l h^{-1} into a suspension of the Grignard reagent prepared from magnesium (0.14 g, 5.8 mmol) and ethyl bromide (0.42 g, 3.9 mmol) in THF (100 ml). The resulting solution was cooled in ice and stirred as a solution of 2-(1,3-dioxolan-2-yl)ethanal (0.3 g, 2.6 mmol) in dry THF (50 ml) was added dropwise during 45 min. The mixture was stirred at room temperature during 24 h. Cold saturated aqueous ammonium chloride (40 ml) was added. Conventional work-up gave 1-(1,3-*dioxolan*-2-*yl*)*but*-3-*yn*-2-*ol* (0.33 g, 89%), b.p. 90 °C/20 mmHg (Kugelrohr); $\nu_{max.}$ 3 640 and 2 120 cm^{-1}; δ_H 2.1 (2 H, t, 1-H_2), 2.5 (1 H, d, C≡CH), 3.0 (1 H, s, OH), 3.8—3.9 (4 H, m, 2 × OCH_2), 4.5—4.6 (1 H, td, CHOH), and 5.05 (1 H, t, CH_2CH) (Found: M^+, 142.1561. $C_7H_{10}O_3$ requires M, 142.1564).

A solution of the dioxolanylbutynol (0.33 g, 2.3 mmol), TBDMSCl (1.30 g, 8.6 mmol), and imidazole (0.54 g, 7.9 mmol) in dry DMF (45 ml) was kept for 24 h, and occasionally shaken. Water (50 ml) was added. Extraction with ether, followed by conventional work-up, gave 3-(*dimethyl-t-butylsilyloxy*)-4-(1,3-*dioxolan*-2-*yl*)*but*-1-*yne* (**34**) (0.47 g, 80%), b.p. 90—95 °C/20 mmHg (Kugelrohr); $\nu_{max.}$ 2 120 cm^{-1}; δ_H 0.1 (6 H, s, $SiMe_2$), 0.9 (9 H, s, Bu^t), 1.3 (2 H, t, 4′-H_2), 2.1 (1 H, s, HC≡C), 3.5 (1 H, td, CH_2CH), 3.7 (4 H, d, 2 × OCH_2), and 4.2 (1 H, t, CHO) (Found: $[M - C_4H_9]^+$, 199.3108. $C_9H_{15}O_3Si$ requires m/z 199.2110).

7-[3′-(*Dimethyl-t-butylsilyloxy*)-4′-(1″,3″-*dioxolan*-2″-*yl*)*but*-1′-*ynyl*]*norbornadiene* (**30**).—A solution of 3-(dimethyl-t-butylsilyloxy)-4-(1,3-dioxolan-2-yl)but-1-yne (**34**) (0.51 g, 2.0 mmol) in dry THF (8 ml) was added to a suspension of the Grignard reagent prepared from magnesium (52 mg, 2.2 mmol) and ethyl bromide (215 mg, 2.0 mmol) in THF (14 ml). The mixture was heated at 50 °C during 1 h. Copper(I) chloride (20 mg) was added and the pale green solution was cooled to room temperature. A solution of 7-chloronorbornadiene (**12**) (0.25 g, 2.0 mmol) in THF in (4 ml) was added. The mixture was stirred at room temperature during 30 min, and under reflux during 90 min, cooled, and added to water (50 ml). Conventional work-up *via* extraction with ether gave a dark orange oil (0.45 g), from which was obtained, by short-path column chromatography [silica (10 g); 2% ethyl acetate in light petroleum], (a) recovered alkyne (**34**) (0.28 g, 55%) and (b) 7-[3-(*dimethyl-t-butylsilyloxy*)-4′-(1″,3″-*dioxolan*-2″-*yl*)*but*-1′-*ynyl*]*bicyclo*[2.2.1]*hepta*-2,5-*diene* (**30**) (0.21 g, 68%), $\nu_{max.}$ 2 120 cm^{-1}; δ_H 0.1 (6 H, s, $SiMe_2$), 0.9 (9 H, s, Bu^t), 2.1 (2 H, t, CH_2CH), 3.3 (1 H, s, 7-H), 3.75 (4 H, s, 2 × OCH_2), 3.85 (2 H, q, 1- and 4-H), 4.1 (1 H, dt, 3′-H), 5.1 (1 H, t, CH_2CH), 6.6 (2 H, t, 5- and 6-H), and 6.7 (2 H, t, 2- and 3-H) (Found: M^+, 346.5505. $C_{20}H_{30}O_3Si$ requires M, 346.5501).

Desilylation of compound (**30**) using tetrabutylammonium fluoride followed the procedure for compound (**26**). The *alcohol* (**30**; H instead of $SiMe_2Bu^t$) was obtained as an oil (77%), $\nu_{max.}$ 3 400br (OH) and 2 121 cm^{-1} (C≡C); R_F 0.41 (50% ethyl acetate–light petroleum); δ_H ($CDCl_3$) 2.1 (2 H, t, 4′-H), 2.5 (1 H, d, 7-H), 2.85 (1 H, br s, OH), 3.5 (2 H, m, 1- and 4-H), 3.9—4.1 (4 H, d, 2 × OCH_2), 4.5 (1 H, dtd, 3′-H), 4.9 (1 H, t, CH_2CH), 6.5 (2 H, t, 5- and 6-H), and 6.65 (2 H, t, 2- and 3-H) (Found: M^+, 232.2651. $C_{14}H_{16}O_3$ requires M, 232.2650).

Lithium aluminium hydride reduction of the norbornadiene (**30**; H instead of $SiMe_2Bu^t$) followed the procedure for compound (**26**). The trans-*alkenol* (**32**; H in place of $SiMe_2Bu^t$) was obtained as an oil (74%), $\nu_{max.}$ 3 400br (OH) and 964 cm^{-1} (*trans*-CH=CH); R_F 0.43 (50% ethyl acetate–light petroleum); δ_H($CDCl_3$) 2.25 (2 H, t, 4′-H_2), 3.3 (1 H, d, J 7.5 Hz, 7-H), 3.5 (2 H, m, 1- and 4-H), 3.8 (4 H, t, 2 × OCH_2), 4.7 (1 H, dt, 3′-H), 4.9 (1 H, t, CH_2CH), 5.2 (1 H, t, 1′-H), 5.51 (1 H, dd, 2′-H), 6.5 (1 H, br s, OH), 6.7 (2 H, t, 5- and 6-H), and 6.8 (2 H, q, 2- and 3-H) (Found: M^+, 234.2811. $C_{14}H_{18}O_3$ requires M, 234.2811).

Silylation gave the *silyl ether* (**32**) as an oil (86%), $\nu_{max.}$ 1 595 (C=C) and 960 cm^{-1} (*trans*-CH=CH); R_F 0.4 (50% ethyl acetate–light petroleum); δ_H ($CDCl_3$) 0.10 (6 H, s, $SiMe_2$), 0.95 (9 H, s, Bu^t), 2.25 (2 H, t, 4′-H_2), 3.3 (1 H, d, 7-H), 3.4—3.5 (4 H, tm, 2 × OCH_2), 3.6 (2 H, m, 1- and 4-H), 4.7 (1 H, dt, 3′-H), 4.9 (1 H, t, CH_2CH), 5.1 (1 H, dd, 1′-H), 5.25 (1 H, t, 2′-H), 6.7 (2 H, t, 5- and 6-H), and 6.8 (2 H, t, 2- and 3-H) (Found: M^+, 348.4530. $C_{20}H_{32}O_3Si$ requires M, 348.4529).

7-[3′-(*Dimethyl-t-butylsilyloxy*)*oct*-5′-*en*-1′-*ynyl*]*bicyclo*[2.2.1]*hepta*-2,5-*diene* (**31**).—This was prepared by a Grignard reaction as described for compound (**30**) to give an oil (46%), $\nu_{max.}$ 2 122 cm^{-1} (C≡C); R_F 0.55 [light petroleum (40—60 °C)]; δ_H($CDCl_3$) 0.1 (6 H, s, $SiMe_2$), 0.95 (12 H, s, Bu^t + Me), 2.1 (4 H, m, 4′- and 7′-H_2), 3.2 (1 H, s, 7-H), 3.7 (2 H, q, 1- and 4-H), 4.5 (1 H, dtd, 3′-H), 5.5—5.7 (2 H, m, 5′- and 6′-H), 6.7 (2 H, t, 5- and 6-H), 6.85 (2 H, t, 2- and 3-H [Found: $M^+ - 57$, 271.1517. $C_{17}H_{23}OSi$ requires $(M - 57)$, 271.1517].

Similarly, a standard procedure for desilylation, reduction, and reprotection was followed for conversion of the alkyne (**31**) into the corresponding alkene (**33**). Thus, desilylation of compound (**31**) gave 7-(3′-*hydroxyoct*-5′-*en*-1′-*ynyl*)*bicyclo*[2.2.1]-*hepta*-2,5-*diene* as an oil (91%), $\nu_{max.}$ 3 400 (OH) and 2 120 cm^{-1} (C≡C); R_F 0.61 (50% ethyl acetate–light petroleum); δ_H($CDCl_3$) 0.9 (3 H, t, Me), 2.5 (4 H, m, 4′- and 7′-H_2), 2.9 (1 H, s, OH), 3.4 (1 H, s, 7-H), 3.6 (2 H, m, 1- and 4-H), 4.3 (1 H, dm, (3′-H), 5.5 (2 H, q, 5′- and 6′-H), 6.55 (2 H, t, 2- and 3-H), 6.75 (2 H, t, 5- and 6-H) (Found: M^+, 214.3089. $C_{15}H_{18}O$ requires M, 214.3091). Lithium aluminium hydride reduction gave the *trans*-alkenol (**33**; H in place of $SiMe_2Bu^t$) as an oil (75%), $\nu_{max.}$ 3 400 (OH) and 964 cm^{-1} (*trans*-CH=CH); R_F 0.58 [40% ethyl acetate–light petroleum (40—60 °C)]; δ_H($CDCl_3$) 0.9 (3 H, t, Me), 2.5 (4 H, dt, 4′- and 7′-H_2), 3.4 (2 H, m, 7-H and OH), 3.7 (2 H, q, 1- and 4-H), 4.3 (1 H, tm, 3′-H), 5.3 (2 H, m, 5′- and 6′-H), 5.6 (2 H, td, 1′- and 2′-H), 6.5 (2 H, t, 5- and 6-H), and 6.6 (2 H, 6, 2- and 3-H). Silylation of the product gave the *ether* (**33**) as a pale yellow oil (70%), $\nu_{max.}$ 968 cm^{-1} (*trans*-CH=CH); R_F 0.26 (light petroleum); δ_H($CDCl_3$) 0.1 (6 H, s, $SiMe_2$), 0.9 (12 H, s, Bu^t + Me), 2.4 (4 H, m, 4′- and 7′-H_2), 3.3 (1 H, m, 7-H), 3.8 (2 H, q, 1- and 4-H), 4.4 (1 H, td, 3′-H), 5.2 (2 H, m, 5′-H_2), 5.6 (2 H, td, 1′- and 2′-H), 6.5 (2 H, t, 5-and 6-H), and 6.6 (2 H, t, 2- and 3-H) [Found: $M^+ - C_5H_9$ 261.1671. $C_{21}H_{34}OSi$ requires $(M - C_5H_9)$, 261.1673].

Typical Procedures for Rearrangement of 7-Substituted Norbornadienes followed by Hydrolysis.—Two procedures were followed: in one method the 4-*exo*-substituted bicyclo[3.1.0]-hex-2-ene-6-*endo*-carbaldehyde (in equilibrium with its enol ether) was isolated by chromatography and characterised by n.m.r. and mass spectrometry prior to hydrolysis to the cyclopentenylacetaldehyde, while in the second the crude bicyclo-[3.1.0]hexenecarbaldehyde was hydrolysed with hydrochloric acid in methylene dichloride to give the required cyclopent-2-enylacetaldehyde directly. Specific examples are now given.

Preparation of 4-exo-*octylbicyclo*[3.1.0]*hex*-2-*ene*-6-endo-*carbaldehyde* (**2**; R = C_8H_{17}). To a stirred mixture of anhydrous sodium carbonate (1.2 g), methylene dichloride (10 ml), and 7-octylnorbornadiene (**1**; R = C_8H_{17}) (1.0 g, 4.9 mmol) was added peracetic acid (48%; 2 ml) treated with sodium acetate (0.1 g) at 20 °C, and the mixture was stirred for 0.5 h. The reaction mixture was extracted (CH_2Cl_2, 10 ml) and the extract was washed with saturated aqueous sodium hydrogen carbonate (2 × 20 ml). The organic layer was dried

and the solvent was removed at 14 mmHg to yield a pale yellow oil. Column chromatography of this oil on silica gel with light petroleum–ether (4:1) as eluant gave starting material (200 mg) and 4-exo-*octylbicyclo*[3.1.0]*hex*-2-*ene*-6-endo-*carbaldehyde* (**2**; R = C_8H_{17}) (0.51 g, 60% based on unrecovered starting material), $\delta_H(CDCl_3)$ 0.9—1.3 (17 H, br m, n-C_8H_{17}), 1.5—3.0 (3 H, m, 1-, 5-, and 6-H), 3.65 (1 H, m, 4-H), 5.9 (2 H, s, 2- and 3-H), and 9.25 (1 H, d, *J* 6 Hz, CHO); $\nu_{max.}$(film) 2 950, 2 850, 1 700, and 1 460 cm^{-1} (Found: M^+, 220.1826. $C_{15}H_{24}O$ requires *M*, 220.1826).

Preparation of (4-*Hydroxy*-5-*octylcyclopent*-2-*enyl*)*acetaldehyde* (**4**; R = C_8H_{17}).—4-*exo*-Octylbicyclo[3.1.0]hex-2-ene-6-*endo*-carbaldehyde (**2**; R = C_8H_{17}) (2.9 g, 13.2 mmol), 2M-hydrochloric acid (40 ml), and methylene dichloride (40 ml) were stirred together at 20 °C for 96 h. The reaction mixture was extracted with methylene dichloride (100 ml) and the extract was washed with water (100 ml). The organic layer was dried and the solvent was removed at 14 mmHg to yield a pale yellow oil. Column chromatography of this oil on silica gel, and elution with light petroleum–ether (1:1) gave starting material (1.4 g) in the first fractions and the required *product* (**4**; R = n-C_8H_{17}) from the later fractions (1.1 g, 68%), $\delta_H(CDCl_3)$ 1.2 (17 H, m, n-C_8H_{17}), 1.9 (1 H, s, OH), 2.3 (2 H, m, 1- and 5-H), 2.65 (2 H, s, CH_2), 4.5 (1 H, s, 4'-H), 5.85 (2 H, s, 2- and 3'-H) and 9.95 (1 H, s, CHO); $\nu_{max.}$(film) 3 400, 2 900, and 1 720 cm^{-1}; (*m*/*z*, %) 238 (4), 220 (56), and 121 (100) (Found: M^+, 238.1931. $C_{15}H_{26}O_2$ requires *M*, 238.1931).

Preparation of {5-[3'-(*Dimethyl*-t-*butylsilyloxy*)*oct*-1'-*enyl*)-4-*hydroxycyclopent*-2-*enyl*}*acetaldehyde* (**5**).—To a vigorously stirred solution of 7-[3'-(dimethyl-t-butylsilyloxy)oct-1'-enyl]-bicyclo[2.2.1]hepta-2,5-diene (305 mg, 0.918 mmol) and anhydrous sodium carbonate (194 mg, 1.83 mmol) in methylene dichloride (20 ml) at 0 °C was added peracetic acid (40% w/w solution; 0.918 mmol) which had previously been stirred with anhydrous sodium acetate (50 mg). The reaction mixture was stirred at 0—2 °C for 16 h. At this point more peracetic acid (0.53 mmol) and sodium carbonate (200 mg, 1.8 mmol) were added, and the mixture was stirred for a further 4 h. Aqueous sodium sulphite (10 ml) was carefully added to the mixture, followed by careful addition of aqueous sodium hydrogen carbonate (30 ml). Methylene dichloride (40 ml) was added, and the organic phase was separated and washed successively with aqueous sodium sulphite (10 ml), aqueous sodium hydrogen carbonate (10 ml), and water (10 ml). The organic phase was dried, filtered, and evaporated to afford a pale yellow oil. Purification by short-path column chromatography (8 g), with hexane as eluant, afforded starting material (35 mg). Increasing the polarity of the eluant (5% ether in hexane) gave an inseparable mixture of the desired bicyclic aldehyde [**2**; R = CH=CHCH(OSiBu^{t}Me$_2$)C_5H_{11}] and the *endo*-epoxides (**37**) and (**38**) (231 mg). One fraction of almost pure aldehyde (**2**) was isolated and its ^1H n.m.r. spectrum was found to be comparable with that of an authentic sample.

The crude aldehyde (**2**) (221 mg) was dissolved in methylene dichloride (10 ml), and hydrochloric acid (2M; 10 ml) was added. The mixture was stirred for 72 h. Methylene dichloride (40 ml) and water (50 ml) were added, and the organic layer was separated and washed with water (20 ml). The combined aqueous phases were back-extracted into methylene dichloride (2 × 30 ml). The combined organic layers were dried, filtered, and evaporated to afford a pale yellow oil. The oil was subjected to short-path column chromatography [silica (5 g), eluant 5% ethyl acetate in hexane] to afford (i) a mixture of the less polar *endo*-epoxides (**37**) and (**38**) [as an oil (48 mg)], R_F (50% ether in light petroleum); for n.m.r. data see Discussion (Found: M^+, 348.2483. $C_{21}H_{36}O_2Si$ requires *M*, 348.2483), and (ii) the required hydroxy aldehyde (**5**) (121 mg, 41%) as an oil, R_F 0.35 (50% ethyl acetate in hexane); $\nu_{max.}$ 3 590 (OH), 2 730 (CHO), 1 722 (C=O), and 972 cm^{-1} (*trans*-CH=CH); δ_H 0.1 (6 H, s, $SiMe_2$), 0.9 (12 H, m, 4 × Me), 1.2 (1 H, m, 5-H), 1.6 (8 H, m, $[CH_2]_4$), 1.84 (1 H, br s, OH), 2.46—2.72 (2 H, ABX, CH_2CHO), 2.82 (1 H, m, 1-H), 4.1 (1 H, m, 3'-H), 4.6 (1 H, t, 4-H), 5.59 (2 H, m, 1'- and 2'-H), 5.84 (2 H, t, 2- and 3'-H), and 9.80 (1 H, t, *J* 1.5 Hz, CHO) (Found: C, 68.6; H, 10.4. Calc. for $C_{21}H_{38}O_3Si$: C, 68.8; H, 10.45%).

Preparation of 4-exo-*Phenylbicyclo*[3.1.0]*hex*-2-*ene*-6-endo-*carbaldehyde* (**2**; R = Ph).—To a vigorously stirred solution of 7-phenylnorbornadiene (**8**) (1.12 g, 6.65 mmol) and anhydrous sodium carbonate (1.06 g, 10 mmol) in methylene dichloride (50 ml) at 0 °C was added sodium acetate (50 mg). Peracetic acid (40% w/w solution; 0.8 g, 5 mmol) was added dropwise during 10 min. The reaction mixture was stirred at 0 °C for 16 h, when all traces of peracid had disappeared.

Aqueous sodium hydrogen sulphite (50 ml) was added and the mixture was poured into a separating funnel. The organic layer was separated and washed successively with aqueous sodium hydrogen sulphite (50 ml), aqueous sodium hydrogen carbonate (50 ml), and water (2 × 30 ml). The combined aqueous layers were neutralised with solid sodium hydrogen carbonate, and extracted with methylene dichloride (2 × 50 ml), and the organic extracts were washed with water (50 ml) and dried ($MgSO_4$ with addition of a little sodium carbonate). Filtration and evaporation gave a pale yellow oil which was purified by short-path column chromatography (silica, 22 g) with hexane, then 5% ethyl acetate in hexane, as eluant, to afford starting material (276 mg), and the title bicyclic aldehyde (**2**; R = Ph) (650 mg, 70.5%) which crystallised as a pale yellow solid. An analytical sample was recrystallised from ether–light petroleum as a *fragrant yellow solid*, m.p. 66—67 °C (lit.,[18] 67—68 °C); R_F 0.45 (25% ethyl acetate–hexane); $\nu_{max.}$(Nujol) 1 680 (C=O), and 746 and 699 cm^{-1} (phenyl); $\lambda_{max.}$ (ε) (EtOH) 258.5 (500), 259 (400), and 269 nm (300); $\delta_H(CDCl_3)$ 1.92 (1 H, m, 6-H), 2.33 (1 H, m, 5-H), 2.79 (1 H, m, 1-H), 3.98 (1 H, m, 4-H), 5.94 (1 H, m, 3-H), 6.05 (1 H, m, 2-H), 7.20—7.40 (5 H, m, phenyl), and 9.97 (1 H, d, *J* 6.5 Hz, CHO). Small peaks at δ_H 5.0, 5.28, 6.54 were due to enol ether tautomer (Found: C, 84.3; H, 6.8. $C_{13}H_{12}O$ requires C, 84.7; H, 6.7%).

(4-*Hydroxy*-5-*phenylcyclopent*-2-*enyl*)*acetaldehyde* (**4**; R = Ph).—(*a*) The bicyclic aldehyde (**2**; R = Ph) (120 mg, 0.65 mmol) was dissolved in methylene dichloride (10 ml), and hydrochloric acid (2M; 15 ml) was added. The mixture was kept for 68 h, and intermittently shaken. Further methylene dichloride (30 ml) and water (30 ml) were added, and the organic layer was separated and washed with water (2 × 30 ml). The combined aqueous layers were extracted with (CH_2Cl_2; 2 × 30 ml). The combined organic layers were dried, filtered, and evaporated to give a pale yellow oil. This was chromatographed through a short-path column (4 g) with 2—30% ethyl acetate in hexane as eluant to afford recovered starting material (27 mg), an impurity that was not characterised (12 mg), and the title hydroxy aldehyde (**4**; R = Ph) (72 mg, 70.5%) as an oil, R_F 0.48 (50% ethyl acetate–light petroleum); $\nu_{max.}$ (0.5% $CHBr_3$ solution) 3 390br (OH), 2 725sm (CH=O), 1 718 (CH=O), and 755 and 700 cm^{-1} (phenyl); $\lambda_{max.}$ (ε) (EtOH) 259 (300), 262 (300), and 269 nm (250); δ_H 2.28 (1 H, br s, OH), 2.61 (2 H, ABX, CH_2CHO), 2.71 (1 H, t, *J* 7.0 Hz, 5-H), 3.15 (1 H, m, 1-H), 4.85 (1 H, m, 4-H), 5.90 (2 H, m, 2- and 3-H), 7.3 (5 H, m, phenyl), and 9.70 (1 H, t, *J* 1.5 Hz, CHO). Elemental analysis was precluded by rapid air oxidation of the product.

(*b*) To a solution of the bicyclic aldehyde (**2**; R = Ph) (1.80 g, 9.78 mmol) in methylene dichloride (70 ml) was added hydrated oxalic acid (300 mg). The mixture was kept for 88 h, when

further methylene dichloride (100 ml) and water (150 ml) were added and the organic layer was separated and washed with water (100 ml). Evaporation of the solvent gave a yellow foam. Purification by short-path column chromatography (30 g) with 10—50% ethyl acetate in light petroleum as eluant afforded impure starting material (690 mg), followed by the title hydroxy aldehyde (**4**; R = Ph) (1.13 g, 57%), with properties identical with those described under (*a*).

(5-Butyl-4-hydroxycyclopent-2-enyl)acetaldehyde (**4**; R = C_4H_9) and (5-hexyl-4-hydroxycyclopent-2-enyl)acetaldehyde (**4**; R = C_6H_{13}) were also obtained by first chromatographing (on silica) the appropriate bicyclo[3.1.0]hex-2-ene-6-*endo*-carbaldehyde intermediate before hydrolysis. Thus 4-exo-*butylbicyclo*[3.1.0]*hex*-2-*ene*-6-endo-*carbaldehyde* (**2**; R = C_4H_9) (60%) was eluted with light petroleum–ether (4:1), $\delta_H(CDCl_3)$ 0.91 (3 H, t, *J* 4 Hz, Me), 1.4 (6 H, s, 3 × CH_2), 1.73 (1 H, q, *J* 7 Hz, 4-H), 2.1 (1 H, t, *J* 7 Hz, 6-H), 2.68 (2 H, m, 1- and 5-H), 5.85 (2 H, m, 2- and 3-H), and 9.19 (1 H, d, *J* 7 Hz, CHO); signals due to the enol were seen at δ_H 4.54 (br s) and 4.99 (t, *J* 6 Hz) and 5.22 and 6.26 (dd, *J* 6 and 3 Hz); *m/z* 164 (M^+), 149 ($M^+ - CH_3$), 135 ($M^+ - CHO$), and 107 ($M^+ - C_4H_9$) (Found: M^+, 164.1201. $C_{11}H_{16}O$ requires *M*, 164.1201).

4-exo-*Hexylbicyclo*[3.1.0]*hex*-2-*ene*-6-endo-*carbaldehyde* (**2**; R = C_6H_{13}) (46%) was eluted with 10—20% ethyl acetate in light petroleum, R_F 0.65 (30% ethyl acetate in light petroleum); $\delta_H(CDCl_3)$ 0.9 (3 H, br t, Me), 1.3—1.6 (10 H, m, $[CH_2]_5$), 1.7—2.2 (2 H, m, 4- and 6-H), 2.4—2.8 (2 H, m, 1- and 5-H), 5.8 (2 H, br s, 2- and 3-H), and 9.2 (1 H, d, CHO); *m/z* 193 ($M^+ + 1$) and 163 ($M^+ - CHO$) (Found: C, 81.1; H, 10.3. $C_{13}H_{20}O$ requires C, 81.2, H, 10.5%). Hydrolysis of this product with 2M-hydrochloric acid in methylene dichloride gave (5-*hexyl*-4-*hydroxycyclopent*-2-*enyl*)*acetaldehyde* (**4**; R = C_6H_{13}) (60%) as an oil after chromatography, R_F 0.13 (30% ethyl acetate in light petroleum); $\delta_H(CDlC_3)$ 0.9 (3 H, t, Me), 1.1—1.6 (10 H, m, $[CH_2]_5$), 2.0 (2 H, m, CH_2CHO), 2.5 (2 H, s, 1- and 5-H), 4.0 (1 H, t, 4-H) 4.4 (1 H, s, OH), 5.9 (2 H, m, 2- and 3-H), and 9.8 (1 H, t, CHO); $\nu_{max.}$ 1 720 cm^{-1} (Found: C, 74.3; H, 10.7. $C_{13}H_{22}O_2$ requires C, 74.2; H, 10.5%).

The remaining (4-hydroxy-5-substituted cyclopent-2-enyl)-acetaldehydes were obtained by hydrolysis of the crude intermediate from peracetic acid hydrolysis with 2M-hydrochloric acid in methylene dichloride. Thus {5-[3′-(*dimethyl-t-butylsilyl-oxy*)*octa*-1,5-*dienyl*]-4-*hydroxycyclopent*-2-*enyl*}*acetaldehyde* (**58**) (45.5%) was obtained as an oil after chromatography; $\nu_{max.}$ 3 140—3 500, 1 720, and 1 610 cm^{-1}; δ_H 0.0 (6 H, s, $SiMe_2$), 0.9—1.1 (12 H, m, Bu^t + Me), 1.1—1.6 (5 H, m, 4′-H_2, 7′-H_2, and 5-H), 2.5 (2 H, m, CH_2CHO), 2.60 and 2.75 (2 H, m, 1-H and OH), 4.1 (1 H, m, 3′-H), 4.4 (1 H, m, 4-H), 5.5 (4 H, m, 1′-, 2′-, 5′-, and 6′-H), 5.8 (2 H, m, 2- and 3′-H), and 9.8 (1 H, t, CHO) [Found: ($M - C_4H_9$)$^+$, 307.1727. $C_{17}H_{27}O_3Si$ requires *m/z*, 307.1728].

{5-[3′-(*Dimethyl-t-butylsilyloxy*)*oct*-5′-*en*-1′-*ynyl*]-4-*hydroxycyclopent*-2-*enyl*}*acetaldehyde* (**59**) (25.5%) was prepared in a similar manner, $\nu_{max.}$ 3 400 and 1 720 cm^{-1}; $\delta_H(CDCl_3)$ 0.1 (6 H, s, $SiMe_2$), 0.9 (12 H, m, Bu^t + Me), 1.3—1.5 (5 H, m, 4′-H_2, 7′-H_2, and OH), 2.6 (2 H, m, 1- and 5-H), 3.1 (2 H, m, CH_2CHO), 3.9 (1 H, s, 4-H), 4.3 (1 H, dt, 3′-H), 5.7 (2 H, m, 5″- and 6′-H), 5.9 (2 H, m, 2- and 3-H), and 9.8 (1 H, t, CHO) [Found: ($M - C_4H_9$)$^+$, 305.4746. $C_{17}H_{25}O_3Si$ requires *m/z*, 305.4741].

{4-(*Dimethyl-t-butylsilyloxy*)-5-[3′-(*dimethyl-t-butylsilyl-oxy*)*oct*-1′-*enyl*]*cyclopent*-2-*enyl*}*acetaldehyde* (**45**).—To a stirred solution of the hydroxyaldehyde (**5**) (1.2 g, 3.28 mmol) in dry DMF were added dimethyl-t-butylsilyl chloride (0.98 g, 6.56 mmol) and imidazole (0.98 g, 13 mmol). The mixture was kept at room temperature for 6 h and then treated with water (70 ml) and extracted with ether (4 × 50 ml). The combined organic layers were dried and evaporated to give a pale yellow oil. Purification by short-path column chromatography with 2% ethyl acetate in light petroleum as eluant afforded the title bis-silyl aldehyde (**45**) (1.13 g, 72%) as an oil, R_F 0.88 (30% ethyl acetate in light petroleum); $\nu_{max.}$ 1 720 cm^{-1}; $\delta_H(CDCl_3)$ 9.8 (1 H, m, CHO), 5.5—5.9 (4 H, m, 2-, 3-, 1′-, and 2′-H), 4.55 (1 H, m, 4-H), 4.1 (1 H, m, 3′-H), 2.0—2.9 (4 H, m, CH_2CHO, and 1- and 5-H), 1.4 (8 H, m, C_4H_8), 0.9 (21 H, m, 7 × Me), and 0.1 (12 H, s, 2 × $SiMe_2$).

{4-*Dimethyl-t-butylsilyloxy*)-5-[3′-(*dimethyl-t-butylsilyloxy*)-*oct*-1′-*enyl*]*cyclopent*-2-*enyl*}*acetic Acid* (**46**).—A solution of the bis-silyl acetaldehyde (**45**) (190 mg, 0.395 mmol) in ether (5 ml) was treated successively with freshly prepared silver oxide (275 mg, 1.18 mmol) in water (2 ml), and sodium hydroxide (2M; 5 ml), and the mixture was stirred at room temperature for 75 min. Ether (20 ml) was added and the reaction mixture was filtered through Celite, and the filter was washed successively with ether (25 ml) and water (25 ml). The organic layer was washed successively with hydrochloric acid (2M; 2 × 25 ml) and water (2 × 25 ml), and the ether solution was dried and evaporated to afford a brown oil. Purification by short-path column chromatography (5 g) with 5% ethyl acetate in light petroleum as eluant afforded the *title acetic acid* (**46**) (181 mg, 92%) as an oil, R_F 0.32 (10% ethyl acetate in light petroleum); $\nu_{max.}$ 3 500—2 300br (CO_2H) and 1 700 cm^{-1} (C=O); $\delta_H(CDCl_3)$ 0.10 (12 H, m, 2 × $SiMe_2$), 0.90 (21 H, m, 7 × Me), 1.10—1.60 (8 H, m, $[CH_2]_4$), 2.00—2.80 (4 H, m, CH_2CO_2H, and 1- and 5-H), 3.90—4.20 (1 H, m, 3′-H), 4.45—4.65 (1 H, m, 4-H), 5.45—5.70 (2 H, m, 1′- and 2′-H), 5.75—6.00 (2 H, m, 2- and 3-H), and 11.00 (1 H, br s, CO_2H) [Found: ($M - 57$)$^+$, 439.2698. $C_{23}H_{43}O_4Si_2$ requires *m/z* 439.2698].

7-endo-(*Dimethyl-t-butylsilyloxy*)-6-exo[3′-(*dimethyl-t-butylsilyoxy*)*oct*-1′-*enyl*]-8-exo-*iodo*-2-*oxabicyclo*[3.3.0]*octane*-3-*one* (**47**).—To a solution of the acetic acid derivative (**46**) (160 mg, 0.32 mmol) in a mixture of ether (8 ml) and aqueous sodium hydrogen carbonate (8%; 8 ml) were added iodine (122 mg, 0.48 mmol) and potassium iodide (239 mg, 1.44 mmol). The reaction mixture was stirred for 18 h. Aqueous sodium hydrogen sulphite (25 ml) and ether (25 ml) were then added in turn, and the organic phase was washed with water (25 ml). The combined aqueous layers were back-extracted with ether (2 × 20 ml), and these layers were washed with water (20 ml). The combined organic layers were dried and evaporated to afford a yellow gum. The product was purified by short-path column chromatography (5 g) with 2% ethyl acetate in light petroleum as eluant to afford the *iodo lactone* (**47**) as an oil (product turned light pink on storage) (164 mg, 82%), R_F 0.5 (15% ethyl acetate in light petroleum); $\nu_{max.}$ 2 900, 1 780 (C=O), 1 470, 1 300, 1 225, 1 150, 910, and 840 cm^{-1}; δ_H 0.10 (12 H, m, 2 × $SiMe_2$), 0.90 (21 H, m, 7 × Me), 1.10—1.80 (8 H, m, C_4H_8), 2.00—2.98 (4 H, m, 4-H_2 and 5- and 6-H), 4.00—4.28 (3 H, m, 3′-, 7-, and 8-H), 5.00—5.25 (1 H, m, 1-H), and 5.45—5.70 (2 H, m, 1′- and 2′-H) [Found: ($M - C_4H_9$)$^+$, 565.1666. $C_{23}H_{42}IO_4Si_2$ requires *m/z*, 565.1666] (Found: C, 52.0; H, 8.3. $C_{27}H_{51}IO_4Si_2$ requires C, 52.1; H, 8.25%).

7-endo-(*Dimethyl-t-butylsilyloxy*)-6-exo-[3′-(*dimethyl-t-butylsilyloxy*)*oct*-1′-*enyl*]-2-*oxabicyclo*[3.3.0]*octan*-3-*one* (**48**).—A few crystals of azoisobutyronitrile were added to a solution of the iodo lactone (**47**) (156.2 mg, 0.25 mmol) in dry benzene (10 ml). The mixture was shaken and a solution of tri-n-butyltin hydride (182 mg, 0.627 mmol) in absolute ethanol (3 ml) was added and the mixture was heated under reflux under nitrogen for 20 min. The reaction mixture was cooled and the solvents were evaporated off under reduced pressure. The product was purified by short-path column chromatography (3.5 g) with 5% ethyl acetate in light petroleum as eluant to

afford the title lactone (**48**) (121 mg, 97%) as a white crystalline solid, m.p. 41 °C; R_F 0.3 (15% ethyl acetate in light petroleum); $\nu_{max.}$ 1 780 (C=O); $\delta_H(CDCl_3)$ 0.1 (12 H, several s, 2 × $SiMe_2$), 0.9 (21 H, m, 7 × Me), 1.10—1.50 (8 H, m, C_4H_8), 1.85—2.05 (1 H, ddd, *J* 12.0, 7.0, and 2.0 Hz, 6-H), 2.15—2.80 (5 H, m, 5-H, 8-H_2, and CH_2CO_2), 3.82—4.20 (2 H, m, 3'- and 7-H), 4.95 (1 H, ddd, *J* 12.0, 7.0, and 2.5 Hz, 1-H), 5.24—5.40 (1 H, ddd, *J* 15.0, 7.0, and 2.5 Hz, 1'-H), and 5.40—5.55 (1 H, ddd, *J* 15.0, 6.0, and 2.0 Hz, 2'-H); n.m.r. and i.r. data correspond to literature values, but the compound was previously reported[21] as an oil.

Preparation of {4-*Acetoxy*-5-[3'-(*dimethyl-t-butylsilyloxy*)-*oct*-1'-*ynyl*]*cyclopent*-2-*enyl*}*acetaldehyde* (**49**).—To a solution of {5-[3'-(dimethyl-t-butylsilyloxy)-oct-1'-ynyl]-4-hydroxycyclopent-2-enyl}acetaldehyde (**41**)[13] (250 mg, 0.69 mmol) in methylene dichloride (10 ml) was added acetic anhydride (13 ml) followed by pyridine (0.3 ml). After 24 h, the reaction mixture was extracted with methylene dichloride (3 × 25 ml) and the extract was washed with saturated aqueous sodium hydrogen carbonate (20 ml), dried, and evaporated to give an oil (255 mg). Flash chromatographic purification with ethyl acetate in hexane (50:50) as eluant afforded the *title product* (**49**) (250 mg, 91%) as a pale yellow oil, R_F 0.73 (50% ethyl acetate in hexane); $\nu_{max.}$ 1 650 (C=C) and 1 720 cm^{-1} (C=O); δ_H 0.1 (6 H, s, $SiMe_2$), 0.9 (12 H, s, 4 × Me), 1.2—1.6 (8 H, m, C_4H_8), 2.1 (3 H, s, OCOMe), 2.3 (2 H, m, CH_2CHO), 2.7 (2 H, q, 1'- and 5-H), 3.7 (1 H, dd, 4-H), 4.3 (1 H, dt, 3'-H), 5.9 (2 H, m, 2- and 3-H), and 9.84 (1 H, t, CHO) (Found: M^+, 406.6428. $C_{23}H_{38}O_4Si$ requires *M*, 406.6430).

Preparation of 2-[4-*Acetoxy*-5-(3'-*hydroxyoct*-1'-*ynyl*)*cyclopent*-2-*enyl*]*acetic Acid* (**50**).—To a solution of {4-acetoxy-5-[3-(dimethyl-t-butylsilyloxy)oct-1'-ynyl]cyclopent-2-enyl}acetaldehyde (**49**) (250 mg, 0.615 mmol) in absolute ethanol (4 ml) was added a solution of silver nitrate (0.25 g) in distilled water (0.4 ml). To this stirred mixture was added dropwise aqueous potassium hydroxide (1M; 4 ml). The heterogeneous mixture was stirred for an additional 2 h, and was then filtered and the silver salts were washed with an equal volume of water. The basic solution was extracted with ether (8 × 20 ml) and the washings were discarded. The basic aqueous phase was made acidic with 2M-hydrochloric acid and extracted with chloroform. The extracts were washed once with a small volume of water, dried, and evaporated under reduced pressure to give an oil (185 mg). Flash chromatography with ethyl acetate in hexane (9:10) as eluant afforded the *title product* (**50**) (183 mg, 96.5%) as a pale yellow oil, R_F 0.28 (90% ethyl acetate in hexane); $\nu_{max.}$ 3 400br (CO_2H, OH), 1 600 (C=C), and 1 725 cm^{-1} (C=O); δ_H 0.9 (3 H, t, Me), 1.1—1.8 (8 H, m, C_4H_8), 2.1 (5 H, d + s, OCOMe and CH_2), 2.5 (1 H, t, 5-H), 3.0 (1 H, tt, 1-H), 4.3 (1 H, tm, 3'-H), 4.75 (1 H, t, 4'-H), 5.87 (2 H, s, 2- and 3-H), and 6.0—6.5 (2 H, br s, 2 × OH) (Found: C, 66.2; H, 7.8. $C_{17}H_{24}O_5$ requires C, 66.2; H, 7.85%).

Preparation of 6-*exo*-(3'-*Hydroxyoct*-1'-*ynyl*)-2-*oxabicyclo*-[3.3.0]*oct*-7-*en*-3-*one* (**51**).—Potassium carbonate (256 mg, 2.61 mmol) was added to a solution of [4-acetoxy-5-(3'-hydroxyoct-1'-ynyl)cyclopent-2-enyl]acetic acid (**50**) (183 mg, 0.59 mmol) in anhydrous THF (5 ml). The mixture was stirred at room temperature for 18 h, and was taken up in chloroform (50 ml) and the organic phase was washed with water (2 × 10 ml). The aqueous layers were extracted with chloroform (2 × 20 ml) and the combined organic extract was dried and evaporated to give an oil (127 mg). Flash chromatographic purification with ethyl acetate in hexane (2:3) as eluant gave the γ-*lactone* (**51**) (125 mg, 85%) as an oil, R_F 0.45 (50% ethyl acetate in light petroleum); $\nu_{max.}$ 3 400 (OH), 2 250 (C≡C), 1 770, 1 720 (C=O), and 1 620 cm^{-1} (C=C); δ_H 0.9 (3 H, t, Me), 1.3 (6 H, m, 5'-, 6'-, and 7'-H_2), 1.6 (2 H, m, 4'-H_2), 2.1 (2 H, m, 4-H_2), 3.0 (1 H, m, 5-H), 3.45 (1 H, s, 6-H), 4.5 (1 H, t, 3'-H), 5.6 (1 H, d, 1-H), and 6.0 (2 H, tt, 7- and 8-H) (Found: M^+, 248.1441. $C_{15}H_{20}O_3$ requires *M*, 248.1412).

Preparation of 7-(5'-*Hexyl*-4'-*hydroxycyclopent*-2'-*enyl*)*hept*-5-*enoic Acid* (**54**).—Potassium t-butoxide (0.63 g) was added to a solution of (4-carboxybutyl)triphenylphosphonium bromide (1.24 g) in THF (20 ml). The mixture was stirred for 20 min to give a bright orange suspension. A solution of the hydroxy aldehyde (**52**) (1.5 g, 7.14 mmol) in anhydrous THF (7 ml) was added and the mixture was stirred for a further 30 min; the solution turned orange-yellow. The mixture was poured into saturated aqueous ammonium chloride (40 ml) and 2M-hydrochloric acid (40 ml) was added. The organic phase was extracted with ethyl acetate (3 × 50 ml), and this extract was washed successively with 2M-hydrochloric acid (30 ml) and brine (2 × 30 ml), and dried. Excess of solvent was removed under reduced pressure to give an oil. Column chromatography over silica (eluant 10—50% ethyl acetate–light petroleum) gave the *title product* (**54**) (1.66 g, 79%) as a pale yellow oil, R_F 0.29 (30% ethyl acetate–light petroleum); $\nu_{max.}$ 3 540br (CO_2H, OH) and 1 720 cm^{-1} (C=O); δ_H 0.9 (3 H, t, Me), 1.3—2.2 (18 H, m, CH_2CH=$CH[CH_2]_3$ and C_5H_{10}), 2.1—2.3 (2 H, m, 1'- and 5'-H), 4.3 (1 H, t, 4'-H), 5.8 (2 H, m, 5- and 6-H), 6.25 (2 H, m, 2'- and 3'-H), 8.8 (1 H, br s, OH), and 9.5—9.7 (1 H, br s, CO_2H) (Found: C, 73.45; H, 10.3. $C_{18}H_{30}O_3$ requires C, 73.4; H, 10.3%).

Preparation of Methyl (5'-*Hexyl*-4'-*hydroxycyclopent*-2'-*enyl*)*hept*-5-*enoate*.—A solution of diazomethane in ether (10 ml) was added to a solution of 7-(5'-hexyl-4'-hydroxycyclopent-2'-enyl)hept-5-enoic acid (**54**) (500 mg, 1.7 mmol) in ether (10 ml). The mixture was kept for 2 h until a yellow colour developed. The excess of solvent was removed under reduced pressure. Short-path column chromatography of the residue over silica (eluant 5—20% ethyl acetate–light petroleum) gave the *title product* (490 mg, 94%) as a pale yellow oil, R_F 0.24 (20% ethyl acetate–light petroleum); $\nu_{max.}$ 1 730 cm^{-1} (C=O); δ_H 0.9 (3 H, t, Me), 1.2—1.5 (10 H, m, $[CH_2]_5$), 2.2 (8 H, m, CH_2CH=$CH[CH_2]_3$), 2.0—2.45 (2 H, m, 1'- and 5'-H), 3.75 (3 H, s, CO_2Me), 4.40 (1 H, q, 4'-H), 5.35 (2 H, dt, 5- and 6-H), 5.75 (2 H, d, 2'- and 3'-H), and 8.3 (1 H, br s, OH) (Found: C, 73.8; H, 10.4. $C_{19}H_{32}O_3$ requires C, 74.0; H, 10.5%).

Preparation of Methyl 7-(5'-*Hexyl*-4'-*oxocyclopent*-2'-*enyl*)-*hept*-5-*enoate* (**56**).—Collins' reagent (0.3 g, 0.98 mmol) was added to a solution of the above hydroxy ester (150 mg, 0.49 mmol) in dry ether (10 ml). The mixture was stirred for 2 h, water (15 ml) was added, the organic phase was extracted with ether (3 × 20 ml), and the extract was dried. Filtration, and evaporation of the excess solvent, gave an oil. Short-path column chromatography over silica (eluant 10—25% ethyl acetate–light petroleum) afforded the *title product* (**56**) (85 mg, 57%) as a pale yellow oil, $\nu_{max.}$ 1 720 and 1 730 cm^{-1} (C=O); δ_H 0.9 (3 H, t, Me), 1.4 (10 H, m, $[CH_2]_5$), 2.3 (8 H, m, CH_2CH=$CH[CH_2]_3$), 2.5 (2 H, dt, 1'- and 5'-H), 3.8 (3 H, s, CO_2Me), 5.4 (2 H, dt, 5- and 6-H), 5.7 (1 H, dd, 3'-H), and 6.2 (1 H, dd, 2'-H) (Found: M^+, 306.4401. $C_{19}H_{30}O_3$ requires *M*, 306.4403).

Methyl 7-(4'-*Hydroxy*-5'-*phenylcyclopent*-2'-*enyl*)*hept*-5-*enoate*.—Potassium t-butoxide (0.72 g, 6.38 mmol) was added to a stirred solution of 4-carboxybutyltriphenylphosphonium bromide (3.26 mmol, 1.4 g) in dry THF (20 ml). The resulting bright orange solution was stirred for 20 min and a solution of the aldehyde (**53**)[18] (150 mg, 0.74 mmol) in dry THF (10 ml) was added. The resulting pale brown reaction mixture was stirred for 20 min and worked up by addition of aqueous ammonium

chloride (10 ml) and hydrochloric acid (2M; 10 ml), followed by extraction of the product with ethyl acetate. Evaporation of the solvent gave a yellow gum which was eluted through a short column of silica with 20—50% ethyl acetate in hexane to give the acid (**55**) (191 mg) contaminated with triphenylphosphine oxide; R_F 0.25 (ethyl acetate in hexane); $\nu_{max.}$ ($CHBr_3$ solution) 3 580, 3 500, and 1 740 cm^{-1}; δ_H 1.62 (2 H, m, 3-H_2), 2.08 (2 H, m, 4-H_2), 2.20 (2 H, t, 7-H_2), 2.26 (2 H, t, 2-H_2), 2.70 (2 H, m, 1'- and 5'-H), 4.80 (1 H, m, 4'-H), 5.45 (2 H, m, 5- and 6-H), 5.80 (1 H, m, 2'-H), 5.92 (1 H, m, 3'-H), and 7.26 (5 H, m, phenyl). The presence of triphenylphosphine oxide was indicated by a signal at δ_H 7.63.

The impure acid (**55**) was methylated with diazomethane in ether and the *title methyl ester* (122 mg, 55%) was purified by short-path column chromatography and elution with 5—10% ethyl acetate in hexane, $\nu_{max.}$ ($CHBr_3$ solution), 3 600, 1 730, and 755 cm^{-1}; δ_H 1.62 (2 H, m, 3-H_2), 2.02 (2 H, q, 4-H_2), 2.20 (2 H, t, 7-H_2), 2.25 (2 H, t, 2-H_2), 2.42 (1 H, br s, OH, 2.70 (2 H, m, 1'-and 5'-H), 3.63 (3 H, s, CO_2Me), 4.76 (1 H, m, 4'-H), 5.30—5.45 (2 H, m, 5'-and 6'-H), 5.75 (1 H, m, 2'-H), 5.95 (1 H, m, 3'-H), and 7.25 (5 H, m, phenyl) [Found: C, 75.65; H, 8.1. $C_{19}H_{24}O_3$ requires C, 76.0; H, 8.0%. C.I. mass spectrum; *m/z*, 318.2084. $C_{19}H_{24}O_3 \cdot NH_4$ ($M + NH_4$) requires *m/z*, 318.2068].

Preparation of Methyl 7-(4'-(Oxo-5'-phenylcyclopent-2'-enyl)hept-5-enoate (**57**).—To a solution of the hydroxy prostanoid (**55**) (400 mg, 1.3 mmol) in dry methylene dichloride (15 ml) at 0 °C was added freshly prepared Collins' reagent (1.4 g, 5.3 mmol). After the solution had been stirred for 30 min at 0 °C more Collins' reagent (400 mg) was added and the mixture was stirred at 0 °C for a further 20 min. The reaction mixture was filtered through Kieselguhr, the residue was marked with methylene dichloride, and the solution was washed successively with 2M-hydrochloric acid (60 ml) and water (60 ml). Drying, filtration, and evaporation gave a brown gum which was subjected to medium-pressure chromatography (silica, Art. 9385; 15 g) with 15% ethyl acetate–cyclohexane as eluant to afford the *title product* (**57**) as an oil (296 mg, 75%), R_F 0.4 (20% ethyl acetate–hexane); $\nu_{max.}$ ($CHBr_3$ solution) 1 720 (C=O, ester), 1 700 (C=O, ketone), 1 586 (C=C–C=O), 1 490, and 750 cm^{-1} (phenyl); δ_H 1.70 (2 H, quintet, 3-H_2), 2.09 (2 H, q, *J* 7 Hz, 4-H_2), 2.32 (2 H, t, *J* 7 Hz, 7-H_2), 2.40 (2 H, t, *J* 7 Hz, 2-H_2), 3.07 (1 H, m, 1'-H), 3.13 (1 H, m, 5'-H), 3.66 (3 H, s, CO_2Me), 5.2—5.6 (2 H, m, 5- and 6-H), 6.26 (1 H, dd, *J* 6 and 2 Hz, 3'-H), 7.09 (2 H, d, *J* 6 Hz, *ortho*-H), 7.2 (3 H, m, *meta*- and *para*-H), and 7.72 (1 H, dd, *J* 6 and 2 Hz, 2'-H) (Found: C, 76.05; H, 7.3. $C_{19}H_{22}O_3$ requires C, 76.45; H, 7.45%).

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